

# **Astrometry, Astrophysics, Precise Time, and Time Interval**

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## **LONG-TERM GOAL**

This program develops, implements, and tests, on telescopes and precise time systems, technologies for the determination of the positions and motions of celestial bodies, the motions of the Earth, and precise time in order to provide the astronomical and timing data required by the Navy and other components of the Department of Defense (DoD) for navigation, precise positioning, command, control, and communications, as well as developing sensor systems for surveillance. The primary goal of this technology development is to improve the accuracy, quantity, timeliness, and reliability of the operational support provided by the U.S. Naval Observatory (USNO) to DoD in the areas of precise time and time interval, Earth rotation and orientation, and inertial reference frames based on star, planet, and extragalactic source positions. Further technologies will be developed to improve sensor technologies for surveillance, targeting, and navigation.

## **OBJECTIVES**

The central objective of this program is to enable the USNO, as the only U.S. institution engaged in the practical application of astrometry and timekeeping, to provide DoD with precise time and celestial position data and also to promulgate such data as directed by public law through the publication of the astronomical ephemeris. The R&D supported by this area allows the USNO to fulfill its operational mission responsibilities in a field which has an ever evolving technology in sensors, communications, systems control, and analysis.

## **APPROACH**

This program enables the USNO to supply quality data operational products to meet DoD and civilian customers' requirements. Specific objectives of this program include:

- Improvement of the U.S. Master Clock systems by evaluating and incorporating new types of clocks, real-time clock monitoring systems, and time scale algorithms for clock ensembles,
- evaluation and refinement of various time transfer (clock synchronization) techniques in order to provide and sustain a tightly coupled worldwide DoD time system,
- improvements to the fundamental ephemerides which are the bases for positions of solar system bodies and the fundamental stellar reference system,

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- improvements to the algorithms for artificial satellite motions which are the bases for the catalog of all artificial satellites,
- improvement in the models and algorithms used for Earth rotation and orientation predictions to fulfill DoD systems autonomy requirements,
- improvements to astronomical reference frames based on star, planet, and quasar positions, including increases in precision, benchmark density, and inertial stability,
- development of radio/IF/optical interferometry and charge coupled device (CCD) technology for precision astronomical measurements, including satellite tracking applications, and
- expansion of precision star catalogs to the infrared wavelengths by exploiting IR technology.

The performance and reliability of new types of clocks (frequency standards), including long-term stability and reliability, must be assessed before such clocks are considered for inclusion in the Master Clock system. Various methods of time transfer--worldwide clock synchronization--must be evaluated. GPS common view provides synchronization at the 10-20 nanosecond level, but other methods, including carrier phase GPS tracking, laser reflection, fiber transmission, global broadcasting and two-way radio transmissions, in some cases have demonstrated the ability to provide synchronization at the nanosecond, or better, level. These techniques need further refinement for use in operational systems.

Very Long Baseline (radio) Interferometry (VLBI) provides the basic data on the orientation and rotation of the Earth. Improvements to the data analysis models for VLBI Earth orientation need to be pursued. The geophysics of the irregularities in Earth rotation are not sufficiently well known to permit predictions that meet the GPS 60-day autonomy requirement. The exploitation of GPS data has been explored for reduced dependence on VLBI measurements and has transitioned into 6.4.

Improvements to astronomical reference frames require new observing and data analysis techniques to be developed, including exploitation of interferometry and charge coupled devices (CCDs). The Navy Prototype Interferometer at Anderson Mesa, AZ is developing this technique for high precision astrometric positions of bright stars. This research is taking place with 6.4 funding and is in its final phase of transition into operations. However, the exploitation of this technique at IR wavelengths needs to be carried out. CCD device applications to astrometry are underway. These devices, of high quantum efficiency, dynamic range, and linear response, promise to revolutionize many types of astronomical observations. Development of hardware and software for CCD detection systems suitable for high precision star positions is a major focus of work at USNO's Flagstaff station. Experimentation and exploration of developing mosaics of CCDs bonded to a single silicon substrate for ultrahigh accuracy relative astrometry are leading to in-house capabilities for accomplishing such exacting tasks. Such mosaics will be used to measure the positions of bright objects relative to distant background objects several hundred thousand times fainter. This project, at the absolute forefront of technology, has the objective of creating a unified inertial stellar reference system covering a brightness range of one million. A new approach to determine very accurate star positions with such detectors on a stationary telescope, the Sloan Digital Sky Survey, covering the one quarter of the entire sky, is being investigated.

## WORK COMPLETED

The cesium atomic fountain project saw several milestones in FY98. Most of the progress was in the area of atomic collection, cooling, and launching. The milestones built on our observation of trapped atoms in a magneto-optical trap (MOT) from the previous fiscal year. This trap is loaded from a background vapor of cesium atoms in a vacuum chamber, and consists of a tailored magnetic field and six laser beams.

After the experiment was put under computer control, we were able to go further with our atom trapping and cooling. The MOT was transferred to both optical molasses and optical lattices for further cooling down to effective temperatures of 1.5 millionths of a degree above absolute zero (microkelvin).

An atomic fountain is based on a cold atom source and a mechanism to launch these atoms upward without significant heating. A second milestone was the demonstration of launching the atomic sample. We were able to perform the first ever demonstration of launching atoms with a four beam optical lattice with good launch velocities and temperatures as cold as 2 microkelvin.

In FY 99 this program will accomplish the following:

The first part of the fiscal year will see us move into our permanent laboratory. This new space will have the required space to allow assembly of the final atomic fountain device. The bulk of the work will be in finalizing the designs for and building the upper region of the experiment in the new lab space. This section of the experimental apparatus will contain the microwave interrogation cavity and magnetic shielding, as well as all of the monitoring, environmental control, and microwave electronics.

Two-way time transfer using communication satellites has been successfully shown to link precise time reference systems at accuracies of order one nanosecond. A program to develop GPS carrier phase technology for time transfer will be initiated in FY99. This technique has the capability of transferring time at precision of 50 picoseconds.

In the area of Earth rotation and reference systems, images of extragalactic radio sources used for determining UT1 were made with the Very Long Baseline Array (VLBA). The purpose of this investigation was to ascertain the limitation on precise source position registration caused by the time varying spatial structure of the radio emission. Sources with inappropriate source structure were removed from the list of sources used for determining UT1, improving the reliability of the radio measurements for UT1. Correction for the effects of source structure was undertaken.

Progress was made in determining earth rotation parameters from GPS observations. The determination of polar motion was successfully demonstrated and is now carried out operationally. The determination of UT1 via GPS observations is difficult because of the inclination of the satellite orbits. It is very difficult to separate orbital precession from variations on the earth's rotation. At the present time, UT1 determinations using GPS appear to be stable for periods of a week or less. This technology effort has transitioned into 6.4 for a demonstration of operational effectiveness.

Acquisition and testing of large-format CCD detectors is continuing. At optical wavelengths work is continuing to develop a large format focal plane array consisting of 30 2056x2056 arrays and 22 2056x400 CCD arrays. This focal plane array is now capable of mapping large areas of the sky to very faint magnitudes. This program, the Sloan Digital Sky Survey (SDSS), is in cooperation with several

major universities, Fermi Lab and Japanese scientist whose purpose is to do astrophysics. This \$80 million program is being leveraged to develop large focal plane array technology for the astrometric needs of DOD. Some of the hardware and all of the software for astrometry are being developed under this program. A 1.3 m telescope is in fabrication and will be equipped with six 2056 x 2056 CCDs for mapping the sky and a variable clock rate CCD for tracking satellites. The camera is nearing completion.

Astrometry at IR wavelengths is being developed. A current generation near-IR camera system based on a Rockwell 256x256 HgCdTe array was delivered in May of 1994 has successfully made observations. It appears, as expected, that the atmosphere is more benign to astrometric observations at a wavelength of 2 microns than at optical wavelengths of 0.5 microns. This has been demonstrated since the telescope point spread function appears to be sharper at 2 microns. Astrometric positions across the 4 arc minute field of the array also appear promising. The development began at Hughes Santa Barbara Research Center on the next-generation near-IR InSb 1024x1024 focal plane array (FPA) that is being jointly funded by USNO and the National Optical Astronomy Observatories is progressing. An array has been fabricated that is about 90% perfect and has obtained observations of many celestial objects at 2 microns. Fabrication of a 99% perfect array is underway. The fabrication of a camera for this array is underway and expected to be completed by October 1997.

Observing programs are continuing for stellar parallaxes with both the TI 800x800 and the Tektronix 2048x2048 CCD detectors. The accuracy of these parallaxes is approaching 0.3 milliarcseconds. This is the highest accuracy thus far achieved for measurements of this type.

## **RESULTS**

The results are summarized in the Work Completed Section of this report.

## **IMPACT/APPLICATION**

In the area of precise time and time interval the stability of the Master Clock is now about 2 parts in  $10^{15}$ . This stability will be improved by an order of magnitude through the use of a Rubidium Fountain. This development will lead to time performance at the 100 picosecond level. Improvements in time transfer at this level are also being developed via GPS carrier phase time transfer. With this long-term stability and accuracy in time it appears promising to achieve worldwide time stability on the nanosecond level and the resulting accuracy in navigation and targeting of precise munitions. In the area of astrometry, the development of large format CCD focal plane arrays will bring forward the determination of precise positions of a large number of stars. This will allow these objects to be employed for the precise determination of satellite positions.

## **TRANSITIONS**

Due to the unique role of the USNO as the standard for Navy and DoD PTTI operations, every successful exploratory development study leads immediately to an improved operational capability. As was stated last year the 6.2 technology development emphasis is shifting to developing improved time standards and time transfer. The successful development of Two Way Satellite Time Transfer in 1996 has allowed the Observatory to link time to the MGS for GPS at a precision of one nanosecond. In the area of earth orientation parameters, the determination of UT1 and polar motion has transitioned from

6.2, via 6.4 into operations. The large InSb focal plane arrays being developed by Hughes Santa Barbara Research Center have transition into 6.4 and will become a standard for all 2 micron applications.

## **RELATED PROJECTS**

This research is highly coordinated with work performed nationally and internationally. The clock work is coordinated with programs at NIST in the US, LPTF and Ecole Normale Supérieure in France and the PTB in Germany. The astrometry work is coordinated with research at universities and national facilities such as the National Radio Astronomy Observatory (NRAO) and the National Optical Astronomy Observatory (NOAO). For example the program to develop the InSb detector array is a joint effort with NOAO. The development of large focal plane arrays for astrometry at optical wavelengths is being pursued in a joint program, the Sloan Digital Sky Survey (SDSS) with the Astrophysical Research Consortium (members Princeton, Universities of Chicago, Washington, Fermilab).